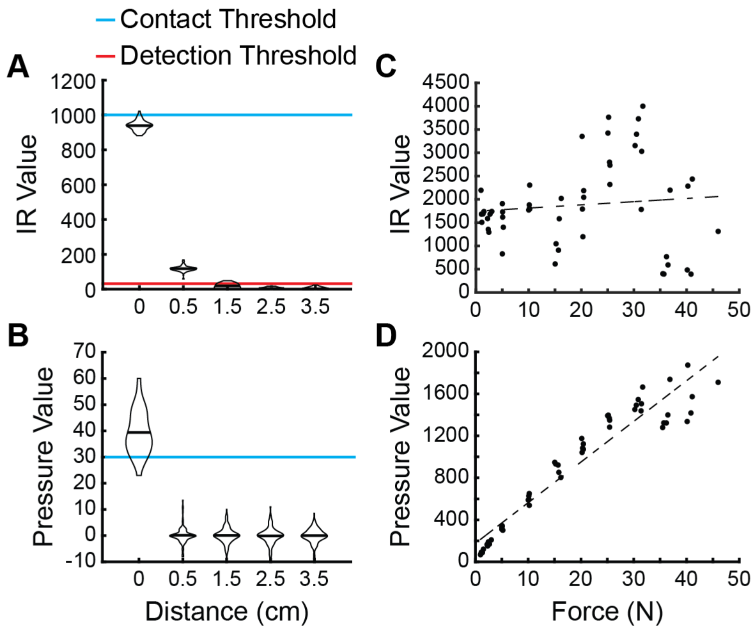
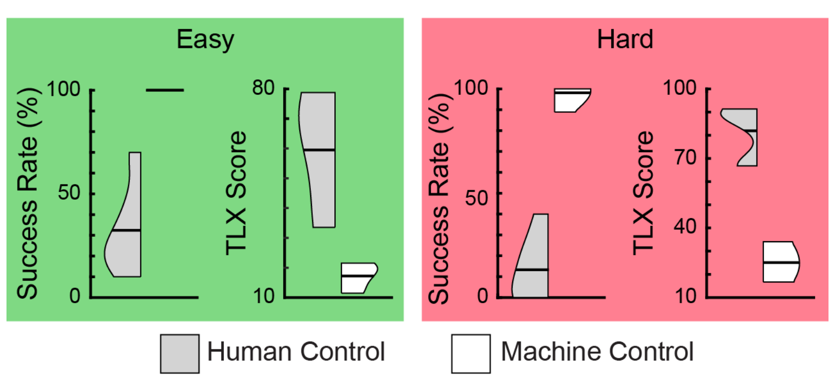
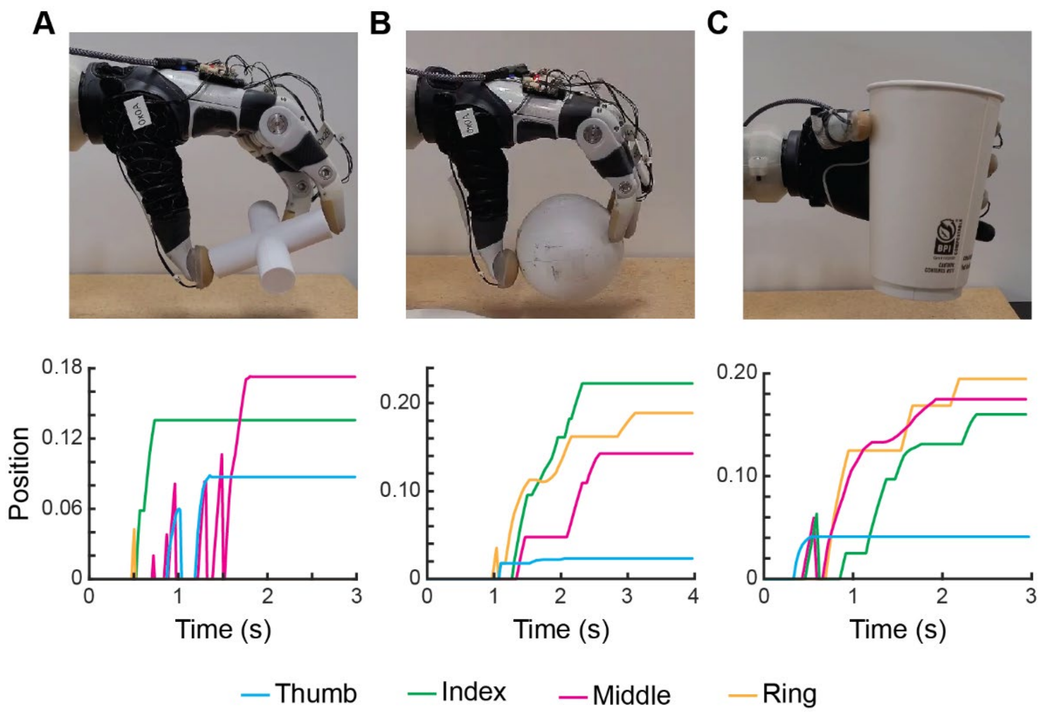
SUPPLEMENTARY MATERIAL



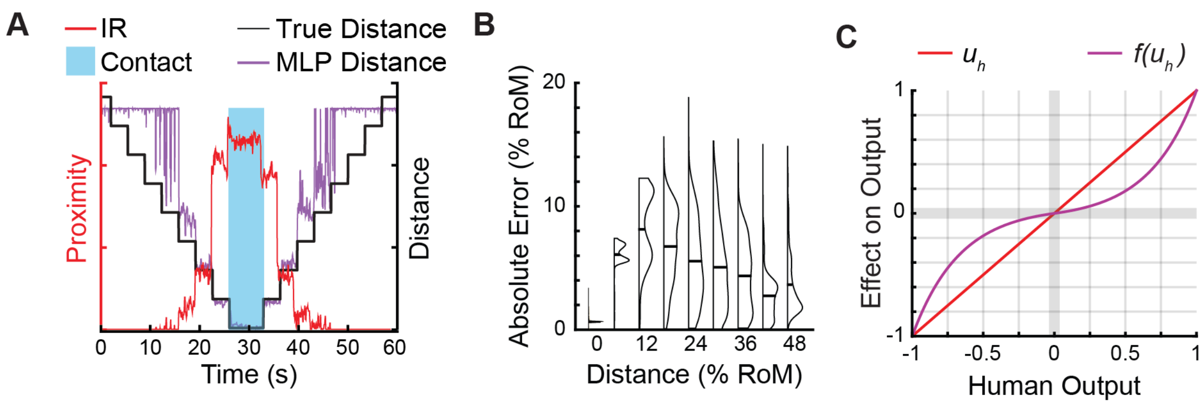
Supplementary Fig. 1: Proximity (IR) and pressure readings under different conditions. A) Proximity sensor readings from a fingertip at different distances from a flat, white surface. A white sheet of plastic was placed in front of a sensorized fingertip at various distances while sensor measurements were recorded for approximately 3 s. The proximity sensor exceeded the noise threshold when the sheet was 1.5 cm or closer. The detection threshold (red line) used for shared control was 30, and contact was detected when the proximity sensor exceeded a value of 1000 (blue line). B) Under the same conditions, the pressure sensor readings were zero-mean until the plastic sheet made contact at the fingertip. Contact could also be detected if the pressure sensor exceeded a value of 30. C) Once the plastic sheet made contact with the fingertip, forces between 0 – 50 N were applied at known levels using a dynamometer while the maximum proximity measurements were recorded. The proximity measurements increased beyond their value at contact, but a linear model fit to the data (red line) had poor accuracy (R^2 = 0.01). D) However, the maximum pressure readings recorded during the same experiment exhibit a strong linear trend up to approximately 30 N (R^2 = 0.91).



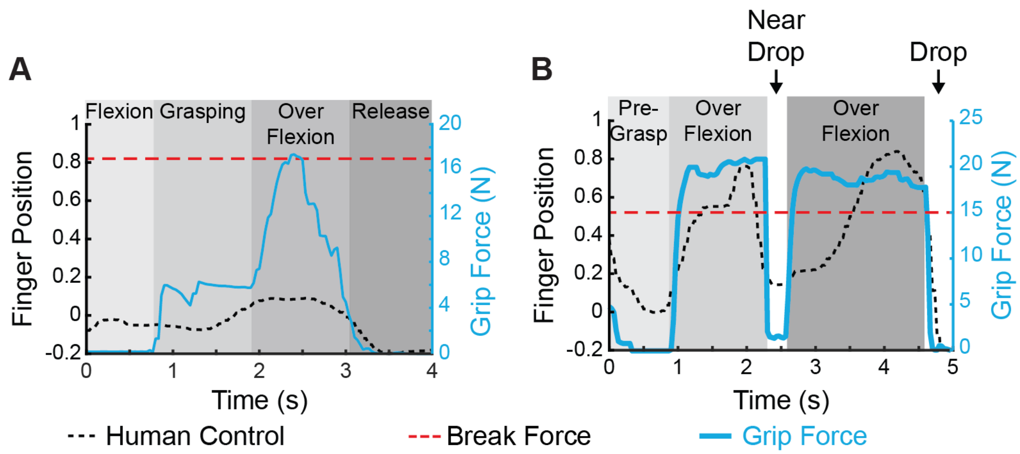
Supplementary Fig. 2: When using the EMG-toggled machine control, participants had a higher success rate for the fragile object transfer task for both the easy difficulty with a fragile break force of 17 N (green) and the hard difficulty, with a break force of 15 N (red). Additionally, participants completed the NASA TLX survey after each experiment and indicated that the machine control was less cognitively demanding than the human control.



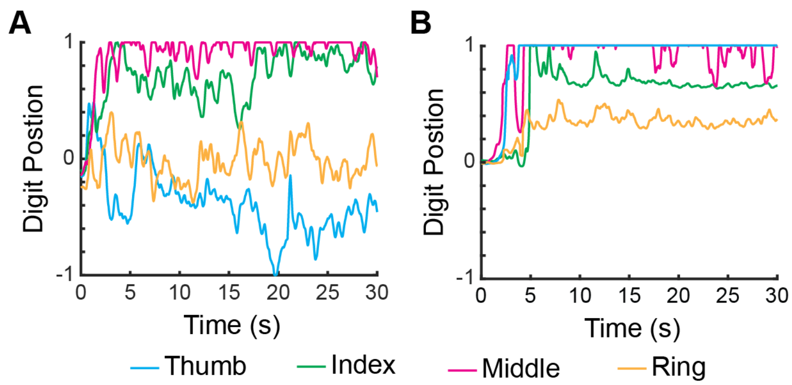
Supplementary Fig. 3: Demonstrations of the machine controller controlling the thumb, index, middle, and ring finger with a cross-bar (A), a ball (B), and a cup (c). The kinematic traces for each digit are displayed beneath the corresponding picture. In each case, the machine controller moved each digit to a unique position such that the hand would lightly grasp each object with each DOF that “saw” the object. While the machine controller was capable of grasping each of the objects in this example, all of the objects were unweighted and relatively lightweight compared to the weighted object used in the experiments.



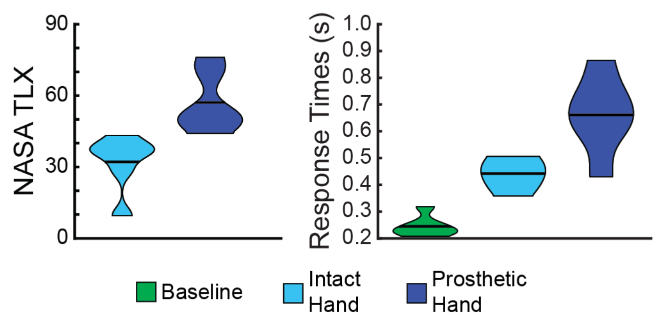
Supplementary Fig. 4: Details of the shared controller. A) The multilayer perceptron (MLP) used for the machine controller was trained by oscillating each digit towards and away from a stationary surface. The MLP was trained to estimate the distance of the fingertip to the point of contact. When the proximity was above the noise threshold, the MLP was able to predict the distance to the object. Data from the MLP training data collected for the thumb sensor. 21,652 distance estimates were compared to the ground truth measurements. B) Validation data from the MLP over the range of the sensors demonstrates that the distance predictions become more accurate as the sensor approaches the object. The sensors could reliably detect a surface within approximately 10% of the range of motion (RoM) of the digits. C) The human controller on its own, u_h (red line), can be difficult to control precise movements that are required to interact with fragile objects, as the user has the same degree of precision throughout the grasp. The shared control algorithm increases the precision of the human controller's contribution by modifying the output with an exponential function, $f(u_h)$ (purple line), about the contact point.



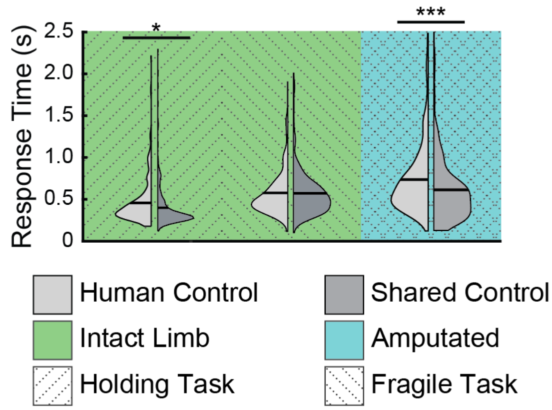
Supplementary Fig. 5: Examples of the human controller interacting with an instrumented fragile object. A) An intact-limb participant controlled a pinch grasp to transfer a fragile object over a barrier without exceeding a break force of 17 N. A Kalman filter decoded 32 sEMG channels to a single DOF. Note how relatively small changes in the decoder's output result in large changes in grip force once the fingers have made contact with the object. B) Using the same method, an amputee participant controlled a one-DOF tripod grasp to hold the instrumented object while maintaining a grip force below 15 N and not dropping the object. Similar to the intact-limb participant, small changes in the decoded grip position resulted in large, fast changes in the grip force, resulting in exceeding the break threshold and dropping the object.



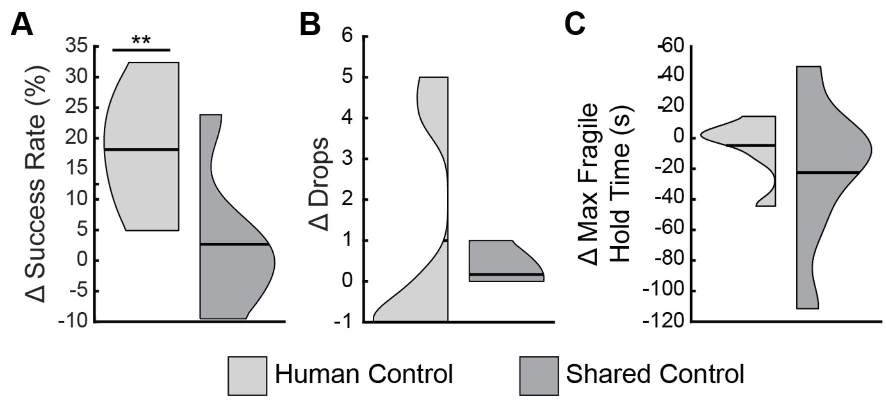
Supplementary Fig. 6: Simultaneous control of four independent digits during the holding task. A) The first 30 s of the most successful trial with human control demonstrates the degree of noise present in the kinematics as decoded from the 32 sEMG channels via a Kalman filter. When using human control, participants had a difficult time controlling all four digits and maintained the grasp by focusing on maintaining the flexed position of any digit that made contact with the object. Note that while the thumb was not flexed, participants were able to hold onto the ball by squeezing it against the palm. B) In contrast, the first 30s of the most successful trial with shared control demonstrate greater stability across all of the digits. The noise observed in the human controller's output is diminished due to the exponential scaling in the shared control framework.



Supplementary Fig. 7: Baseline perceived workload and cognitive load data for six intact-limb participants. Participants completed a baseline detection response task (DRT) alone and then again with a fragile object transfer as a secondary task, followed by completing the NASA TLX survey. The fragile object transfer task was completed using their intact hand or a pinch grasp with a prosthetic hand using human control. The object was considered very difficult to transfer as it broke with a force of 0.7 N. A) From the NASA TLX results, a score of 32.14 ± 11.98 is considered easy as participants successfully transferred the fragile object 100% of trials using their intact hand, and 57.07 ± 12.63 is corresponds to a more difficult task as the success rate was 20% when using a prosthetic hand. The prosthetic hand was controlled via a 1 DOF mKF decoding 32 sEMG channels. B) The participants' baseline response times to the DRT without an additional task were 0.25 ± 0.04 s. Increasing the cognitive burden by introducing the secondary task increased the response time by 0.44 ± 0.06 s, and making the task more difficult by using a prosthetic hand rather than a healthy hand further increased the response time to 0.66 ± 0.15 s.



Supplementary Fig. 8: Detection Response Task (DRT) results from all experiments by participant condition. Differences in the response times to the DRT were observed across the tasks and populations. The intact-limb participants had a slower response time during the fragile-object transfer task than during the holding task. The amputee participants also had slower response times during the fragile-holding task than the intact-limb population had during the non-fragile holding task. However, it is unclear if this is due to the differences in the population or the increased difficulty of the task. * $p < 0.05$; *** $p < 0.001$. Statistical comparisons were performed with a two-sided test using a generalized linear model.



Supplementary Fig. 9: Learning effects across the experiments for both controllers. The main experimental outcomes from the first experimental block were compared to the second experimental block. The resulting distribution was then compared to a zero-mean normal distribution to assess if any potential learning occurred between trials. A) A significant increase in performance between the first and second experimental blocks of the fragile-object transfer task was detected for the human controller ($p < 0.01$, paired t-test), indicating that participants improved their performance with the human controller across the course of the experiment. No significant difference was detected between trials for the shared controller ($p > 0.05$, paired t-test). B) No significant learning effects were detected for the human or shared controller within the holding experiment. C) No significant learning effects were detected for the human or shared controller within the fragile-holding experiment ($p > 0.05$, two-sided paired t-test).

FRAGILE-OBJECT TRANSFER TASK; N = 6 INTACT LIMB PARTICIPANTS			
OUTCOME	Human Control	Shared Control	*p*
SUCCESS RATE (%)	59 ± 23	89 ± 10	$p < 0.01$
MAX FORCE (N)	9.68 ± 4.95	7.60 ± 3.53	$p < 0.001$
TRANSFER RATE (TRANSFER/MIN)	10.08 ± 2.87	9.04 ± 2.92	$p = 0.07$
DRT RESPONSE TIME (S)	0.55 ± 0.26	0.56 ± 0.27	$p = 0.36$
EMG MEAN ABSOLUTE VALUE (μV)	40.28 ± 26.99	40.81 ± 23.64	$p = 0.93$
HOLDING TASK; N = 6 INTACT LIMB PARTICIPANTS			
NUMBER OF DROPS	2.33 ± 3.50	0.25 ± 0.45	$p < 0.05$
MAX HOLD TIME (S)	54.01 ± 46.02	77.61 ± 45.47	$p < 0.05$
FINGERS MAKING CONTACT	2.40 ± 0.48	2.73 ± 0.65	$p = 0.28$
DRT RESPONSE TIME (S)	0.46 ± 0.26	0.40 ± 0.26	$p < 0.05$
EMG MEAN ABSOLUTE VALUE (μV)	60.16 ± 29.57	46.96 ± 8.95	$p = 0.17$
FRAGILE HOLDING TASK; N = 4 TRANSRADIAL AMPUTEE PARTICIPANTS			
FRAGILE HOLD TIME (S)	7.81 ± 12.33	51.56 ± 45.0	$p < 0.01$
GRIP FORCE (N)	14.86 ± 4.54	9.74 ± 4.27	$p < 0.001$
DROPS	9.64 ± 6.46	4.64 ± 4.88	$p = 0.10$
DRT RESPONSE TIME (S)	0.74 ± 0.41	0.62 ± 0.38	$p < 0.001$
EMG MEAN ABSOLUTE VALUE (μV)	49.89 ± 43.28	45.89 ± 39.0	$p = 0.54$

Supplementary Table 1: Numerical results of each experiment.